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POSSIBILITIES OF FORECASTING POLLUTANT CONTENT IN URBAN AIR

(Nekotoryye vozmozhnosti prognoza soderzhaniya primesey v gorodskom vozdukhe)

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POSSIBILITIES OF FORECASTING POLLUTANT CONTENT IN URBAN AIR

L. R. Son'kin

The most significant accumulation of pollutants in the air occurs when increased levels of emission occur during meteorological conditions that are unfavorable for their dispersal. In this connection, it is necessary to forecast such conditions and take measures to prevent excessive emissions.

The development of a forecasting method involves studying the meteorological factors that govern the significant accumulation of pollutants in the layer of air near the ground.

In the case of individual situations, meteorological conditions are known during which increased concentrations of pollutants are observed in the air. This applies in particular to cities where industrial plants are located outside the residential area. Here a necessary condition for increased pollutant content in the air is the correct wind direction. When the wind blows from this direction, the meteorological factors which produce the most intensive accumulation of pollutants in the layer of air near the ground have largely been analyzed in theoretical studies [2-5]. These include a dangerous wind speed, which is a function of the parameters of the emissions, the inversion that exists above the sources, and fogs. On the basis of these relationships, operational meteorological monitoring of industrial plants has been started in some cities (Dzerzhinsk, Zaporozh'ye).

It is a much more complicated problem to define the meteorological conditions for an increased content of pollutants in the air of cities on whose territory a great many different emission sources are located.

Here it is practically impossible to take into account the parameters of the emissions from all of the sources, especially since many of them are random in nature. The problem takes on a statistical nature. In a number of papers [11-16, and others], including studies performed previously by the author [6-9], the relationships existing between the presence of pollutants in the air of cities and the meteorological conditions and synoptic processes have been studied. Individual statistically significant relationships have been found which occur, on the average, in a relatively well defined form, but may have significant exceptions in concrete cases. For the purpose of defining these relationships further, particular emphasis has been placed on studying the meteorological conditions governing the total content of pollutants in the air over the entire city. The parameter

$$P = \frac{m}{n},$$

has been used to characterize it; n is the total number of observations during the time interval in question (one or more days), and m is the number of observations in the same time interval with concentrations in excess of 1.5 times the average seasonal value for each point separately [10]. Obviously parameter P can vary from 0 to 1. On the average, $P \approx 0.2$.

The meteorological conditions governing the pollutant content in the air as a whole above the city are studied individually for different seasons of the year. The present paper contains the results of an analysis of data for the cold half of the year 1967-1968 in the cities of Leningrad, Sverdlovsk, Alma-Ata, Dursk and Krasnoyarsk, and also for two cold halves of the year (1968 and 1968-1969) on the basis of data from Chita. The study of the pollutant content in the air under stagnant conditions also used data from Irkutsk and Novosibirsk for the period from October, 1967 to March, 1968.

The introduction of parameter P may be valuable for clarifying the relationships. As a matter of fact, the information on the concentrations of pollutants in the air contains a random component for a number of reasons, especially due to the aperiodic variations in emissions. This may be also

related to the disturbances of the established relationships. The parameter P is less subject (as compared to values of other concentrations) to the influence of random variations in emissions [10] and is governed to a large extent by meteorological conditions. Hence, when using P, we shall be excluding at least one of the reasons for disruption of the relationships. It has been found, however, that the previously obtained relationships between the meteorological conditions and the content of pollutants in the air is not always realized in specific conditions. For example, it is known that one of the dangerous conditions in cities is stagnation of the air, characterized by very gentle winds (0 - 1 m/sec) and inversions near the ground. An analysis of data from the eight cities mentioned above has shown that the recurrence of increased pollutant content in the air (P > 0.2) under stagnant conditions is only 70%. However, high values for P are frequently found under weather conditions which do not always qualify as unfavorable for large cities.

From this it must be concluded that the above-mentioned disturbances in the statistical relationships are governed, not only by the existence of a random component in the information, but also by the fact that certain important meteorological factors are not taken into account. A further analysis, on the one hand, must involve a more detailed examination of the development of certain relationships and, on the other hand, must involve an attempt to clarify and study these new factors.

First of all, it is interesting to deal with the problem of how the pollutant content in the air varies on the average when the stagnation conditions are disturbed (a combination of calm and inversion near the ground) in conjunction with an increase in wind and breaking up of the inversion, and which of these factors is the most important. It turns out that increasing the wind to 1 - 2 m/sec leads to less of a drop in the pollutant content in the atmosphere than does liquidation of inversion near the ground with continuing calm (Table 1). The Table does not contain data for the city of Kursk, because there were few instances of lack of wind during the period under study.

TABLE 1

INDEX OF THE IMPURITY CONTENT IN THE AIR BY CITIES UNDER NEARLY CALM CONDITIONS

City	Wind Speed (m/sec.) with inversion near the ground			Calm and absence of inversion near the ground
	calm	1	2	
Leningrad	0.27	0.23	0.19	0.14
Sverdlovsk	0.18	0.17	0.18	0.12
Alma-Ata	0.37	0.33	-	0.17
Krasnoyarsk	0.33	0.33	0.30	0.19
Chita	0.25	0.23	0.16	0.20

The results shown in Table 1 correspond to the findings of the theoretical studies of M. Ye. Berlyand [3], from which it follows that dropping of the wind to a calm has a double influence on the pollutant content of the air. On the one hand, the concentration of pollutants in the layer of the atmosphere near the ground will increase considerably. At the same time, however, there is an unlimited increase in the superheated pollutants which are carried up to higher layers of the atmosphere when there is no wind and are dispersed there. However, if the calm is accompanied by an inversion, a ceiling is imposed on the rising pollutants and prevents them from rising further. As a result, the concentrations of pollutants near the ground increase sharply. This is precisely why, as we can see from Table 1, the content of pollutants in the air under calm conditions drops sharply when there is no inversion. When the calm is not accompanied by considerable atmospheric stability, even small amounts of superheated pollutants will be carried up to higher layers, and will not pollute the layer of the air near the ground.

Hence, the existence of calm or gentle winds by itself cannot be viewed as an unfavorable situation. A study of the recurrence of gentle winds as a characteristic for evaluating the potential for pollution of the air in

winter over an extensive territory [1] is justified by the fact that they are most frequently accompanied by stable stratification.

The wind speed and atmospheric stability are not completely responsible for the nature of the pollutant content in the air, and consideration of these parameters alone is insufficient for predicting them. In analyzing other factors, it is natural to consider in particular the wind direction. Analysis of observations of the concentrations of pollutants at scattered points in a number of cities has shown that in most cases the relationship between the pollutant content in the air and the wind direction is not present in such an analysis [6]. This is explained by the characteristics of the propagation of the pollutants in the city: a great many of the sources with different characteristics of emission, a complex wind field, and development of a background concentration. At the present time, while analyzing the values of P which characterize the pollutant content in the air for the city as a whole, it has been found that at certain wind directions the average pollutant content in the urban atmosphere undergoes an increase. This can be seen from Table 2.

Hence, the wind direction may be viewed as one of the independent factors which governs the pollution of air in cities.

Accumulation of pollutants in urban air is a function of the air temperature in the layer of air near the ground: at a relatively high temperature, all other conditions being equal, there will be a high level of air pollution. This is frequently difficult to follow due to the effect of other factors. For example, a considerable accumulation of pollutants is promoted by atmospheric stagnation, which is usually observed at very low temperatures. The appearance of active winter cyclones causes a marked rise in temperature and at the same time leads to purification of the atmosphere with respect to pollutants. Consequently, if we view the relationship between the pollutant concentration in the air and the temperature of the latter independently of other weather conditions, it is usually found that there is a decrease in the pollutant content in the air with increasing temperature rather than an increase, which will be governed by the above mentioned phenomena.

TABLE 2

RECURRENCE OF CASES WITH INCREASED POLLUTANT CONTENT IN THE AIR (P > 0.2) AT SEVERAL WIND DIRECTIONS

City	Unfavorable wind direction	Recurrence (%)
Leningrad	E, SE, S, SW	79
Sverdlovsk	SE, S	68
Kursk	N, NE, E	58
Krasnoyarsk	NE, E	83
Alma-Ata	SE, E	80
Chita	N, NE, E, SE	60

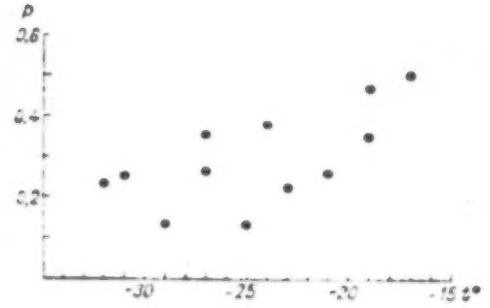

Figure 1. Pollutant content in the air (parameter P) versus daytime temperature under dead calm conditions. Chita.

Hence it is necessary to consider the relationship between air pollution and its temperature when other weather conditions are approximately the same. This has been done on the basis of the data from the cities of Alma-Ata and Chita, where gentle winds predominate and the variations in the meteorological situations are comparatively small. On the basis of the data from the three winter months in Alma-Ata (December 1967, January and February 1968), 18 cases were selected when the inversion near the ground was accompanied by a wind speed of 0 - 1 m/sec. We investigated the relationship between parameter P and the maximum air temperature (t_M) on a given day. It was found that there is a definite positive relationship expressed by the correlation coefficient $r = 0.47 \pm 0.19$. With $t_M > 0$ on the average $P = 0.43$, and when $t_M < 0$, $P = 0.24$.

From the observations at Chita, 12 cases were selected when there was a considerable inversion near the ground under conditions of air stagnation during daytime hours (the thickness of the inversion was at least 500 meters and the intensity was at least 5°). Here the correlation with the air temperature was still closer (Figure 1), $r = 0.66 \pm 0.17$.

The tendency toward an increase in pollutant content in the air at relatively high temperature does not develop under calm conditions alone. Thus, in Leningrad, during winter thaws and gentle winds, the pollutant content in the air was increased ($P > 0.2$) in 7 cases out of 8; in Sverdlovsk air temperature during the winter period above - 10° and a wind speed of 1 - 2 m/sec., it was recorded in 10 cases out of 13. At Krasnoyarsk at an air temperature of more than 8° and a wind speed of no more than 5 m/sec., the increase in the pollutant content in the air was observed in 9 cases out of 11.

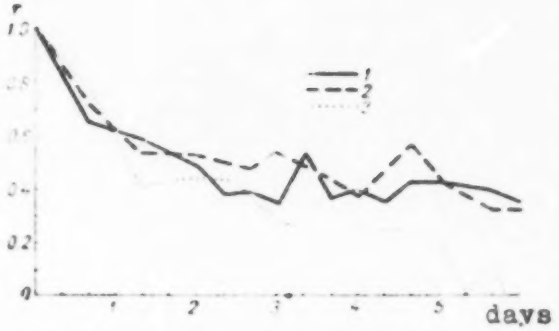

Figure 2. Autocorrelation time function of parameter P.
1 - Krasnoyarsk 2 - Alma-Ata
3 - Chita

Two reasons for the direct relationship of the pollutant content in the urban air and its temperature can be suggested. First of all, under conditions of atmospheric stagnation at low winter temperatures, the heat island effect is intensified, and there is corresponding development in the city of relatively pure air due to local circulation. A similar conclusion was reached by I.A. Zil'bershteyn [5]. The second reason may be related to an increase in the occurrence of superheated emissions with decreasing temperature due to an increase in the temperature differential between the emitted pollutants and the surrounding air.

A significant influence on the pollutant content in urban air is exerted by the inertial factor. The pollutant content in the air for the city as a whole depends to a large extent on its magnitude on the previous days, and in many instances this fact is the reason for the disruption of known relationships.

An analysis of the time correlation function of the values of P was conducted in order to study the inertial factor; P was calculated on the "Ural-4" computer using a specially written program. The function for several cities is shown in Figure 2. In view of the fact that the observations of the pollutant content in the air were conducted using a sliding graph (on Monday, Wednesday and Friday at 1500, 1800 and 2100, and on Tuesday and Thursday and Saturday at 0600, 0900 and 1200), with Sunday off, the intervals in days between the average periods were as follows: 2/3, 1 1/3, 2, 2 1/3, 2 2/3, 3, 3 1/3, 3 2/3, etc. It is evident from Figure 2 that a stable positive correlation is maintained for 4-5 days. In the interval of 2-3 days,

TABLE 3

RECURRENCE (%) OF INCREASED POLLUTANT CONTENT IN THE AIR (P > 0.2) VERSUS PAPAMETER P ON THE PREVIOUS DAY (THE NUMBER OF CASES OF THE CORRESPONDING SAMPLE IS SHOWN IN PARENTHESES)

P_{n-1}	OBSERVATIONS CONDUCTED			
	During the morning of the current day, in the evening of the previous day		In the evening of the current day, in the morning of the previous day	
	In the general case	With stagnant air	In the general case	With stagnant air
< 0.1	11 (105)	24 (33)	24 (66)	50 (10)
> 0.3	92 (109)	95 (39)	66 (75)	100 (14)

r = 0.7-0.8 and in the 4-5 day interval, r = 0.25 - 0.30.

Let us examine the inertial factor in a form which is convenient for use for forecasting purposes.

Table 3 shows the data on the recurrence of instances with an increased air pollution level following different values on the preceding day.

Here we can see the results of calculations for all of the cities in question together. However, the characteristics are given for each of the cities individually.

It is clear from the Table that only the value of the index P on the day in question determines the pollutant content in the urban air on the next day to a significant degree. There is a particularly close relationship which is observed between the pollutant content in the air of the current day on the basis of data from morning observations and for the previous day on the basis of data from evening observations. Table 3 also shows data on the pollutant content in the air under calm conditions as a function of the value P on the

preceding day (P_{n-1}). The most striking fact is the fact that, after a day with clean air ($P_{n-1} < 0.1$) and under calm conditions, there is no increase in the pollutant content. This is related to the majority of cases when the air was calm and comparatively pure. Hence, two types of inertia are seen: meteorological and total pollutant content in the air. Meteorological inertia reflects the tendency toward retention of those atmospheric factors which govern the level of pollutant content in the air. It is important in this case that some may be unknown and can be taken into account automatically to some extent by an examination of the preceding pollutant content in the air. Relatively pure air under calm conditions following a day with low values of P is governed by the inertia of the pollutant content in the air itself.

During periods of calm air, the development of the inertial factor in the manner described above is disrupted. Accumulation of pollutants in the urban air does not occur at these times. According to the data for a number of cities, we managed to find 21 cases of calm air during the winter season with periods of no more than three days duration. It was found that in only two cases, both of which involved a calm lasting only three days, there was a continuous increase in the pollutant content in the air. Table 4 gives an idea of the change in the pollutant content in the air during the periods of calm in question.

Hence, during a period of calm air there are changes in the content of pollutants in the atmosphere with one or more maxima observed, or there is a decrease. Characteristic examples of the pattern of the pollutant content in the air during a period of calm are shown in Figure 3. It is clear that under these conditions, there are factors which prevent a continuous increase in pollutant content in the air. First of all, the occurrence and dispersion of pollutants at a certain moment in time may cause development of dynamic equilibrium, since an increase in the pollutant content in the city leads to simultaneous removal due to an increase in the concentration gradients. Secondly, under calm air conditions, due to the accumulation of pollutants as

TABLE 4

NUMBER OF CASES WITH DIFFERENT CURVES OF POLLUTANT CONTENT IN THE AIR DURING LONG PERIOD OF CALM (THREE DAYS OR MORE)

Total number	Continuous increase	Continuous decrease	One maximum in the middle of the period	2-3 maxima during the period	No Change
21	2	7	4	6	2

well as a temperature decrease (as discussed earlier), the urban heat island effect becomes more manifest and thus leads to a stimulus of turbulent exchange. It has been found that the most dangerous cases are those when a calm develops and there was an increased value for parameter P on the previous day when the situation was not as stagnant. On the basis of data for two winter seasons in the city of Chita, we selected 19 such instances ($P_{n-1} > 0.25$) when P = 0.34 on the average. If the stagnant situation was not observed for the first day, with $P_{n-1} > 0.25$ (according to the data from Chita) the average pollutant congent in the air is not as great — P = 0.28.

Hence, the time of decrease in wind speed to values of less than 1 m/sec and the establishment of air stagnation conditions is dangerous. Under these conditions, on the basis of the data from all of the cities mentioned, there were 12 instances (out of 44) with a very significant pollutant content in the air (P > 0.4). It is clear from these materials that there are a number of reasons of a meteorological nature which govern the concentration of pollutants in urban air. They have a complex relationship with one another and with the characteristics of the dispersal of emissions in the city. However, one can see that there are several meteorological factors which act jointly and simultaneously (to a certain degree) independently, governing the pollutant content in the urban air: wind speed, stability of the boundary layer of the atmosphere, wind direction, temperature of the layer of air near the ground, previous air pollution in the city. The results obtained make it possible to formulate in the first approximation the meteorological conditions for an

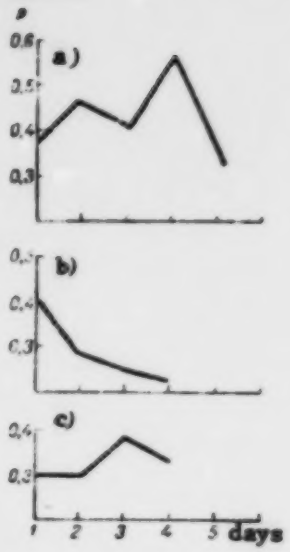

Figure 3. Characteristic types of changes in pollutant content in the air during air stagnation.
(a) Krasnoyarsk, 30 January - 3 February 1968; (b) Chita, 25-28 December 1967; (c) Krasnoyarsk, 6-9 December 1967.

increased pollutant concentration in the air for using the results in forecasting fields. Essentially, we are speaking of the formulation of rules for forecasting pollutant content in the air, inasmuch as the meteorological conditions are forecase systematically.

Rules were formulated for forecasting increased pollutant content in the air as well as rules for forecasting the most dangerous accumulation of pollutants in urban air. In the first case, we are speaking of alternative forecasting of an increased content of pollutants in the air, for which the condition $P > 0.2$ has been assumed. It is clear that such forecasts are of definite interest, although their practical significance is limited. The greatest amount of interest lies in forecasting days with the highest pollutant content in the air, during which there is an actual need to limit the emission and combat the danger posed to human health.

The following meteorological conditions have been defined which govern the increased content of pollutants in the air ($P > 0.2$).

1. Air stagnation (inversion near the ground and wind speeds from 0 to 1 m/sec.).

On the whole, for all the cities in question, the recurrence of instances with $P > 0.2$ is about 70% as we have already said. The highest percentage was noted at Alma-Ata (80%), Krasnoyarsk (78%) and Irkutsk (79%). The rule did not hold in the same way at Sverdlovsk (33%) and Novosibirsk (50%) apparently because of the considerable amount of high emissions for which, as we know, calm does not constitute a dangerous situation.

2. Stagnation of air in conjunction with relatively highly polluted air on the previous day $P_{n-1} > 0.15$.

On the whole, for all of the cities in question, recurrence $P > 0.20$ is found in 88%. This rule is valid in the light of the data from each city individually.

3. Unfavorable wind directions.

In each of the cities studied above, there are 1 or more directions at which the pollutant content in the air is relatively high. The recurrence of cases with $P \geq 0.2$ when the wind blows from such unfavorable directions amounts to 75% in all for all of the cities.

4. An air temperature which is relatively high in comparison to average values and gentle winds.

This condition is very frequent in Leningrad, Sverdlovsk, Krasnoyarsk and Alma-Ata, but the criteria for the different cities are different. For the four cities mentioned above, the recurrence $P > 0.2$ is 80%.

5. The high level of concentration of pollutants in the air on the previous day, provided that no abrupt weather changes are expected, causing purification of the atmosphere with respect to pollutants (occurrence of a developed cyclone, a considerable increase in the pressure gradient, etc.).

If $P_{n-1} > 0.3$ on the previous day, on the following day (on the basis of data from all of the cities in question) and independently of other conditions, the recurrence $P > 0.2$ will be 80%. The need for taking possible abrupt changes in weather into account when using the inertial factor is evident.

Two types of cases must be classified among the neteorological conditions which lead to the most dangerous accumulation of pollutants in urban air.

1. Cases of dangerous accumulation of pollutant in air combined with several of the above-mentioned unfavorable meteorological conditions, including $P_{n-1} \geq 0.25 - 0.30$.

We shall present below the conditions for the most intensive atmospheric pollution for individual cities.

Krasnoyarsk. Calm air or relatively high temperature ($t > 8$) with gentle winds combined with $P_{n-1} \geq 0.3$. During the winter, 14 days were observed that met these conditions, including all instances of the most intensive pollutant content in the air.

Alma-Ata. Calm air with a positive maximum temperature in the daytime combined with $P_{n-1} \geq 0.30$. Eight days on which these conditions prevailed included all cases with the most dangerous accumulation of pollutant in the air.

Leningrad. A gentle wind (up to 2 m/sec.) from unfavorable directions (E, SE, SW), combined with inversion near the ground. There were 16 days with these conditions and they included all of the dangerous situations. If we pose the additional condition $P_{n-1} \geq 0.30$, there would be only six days with very intensive pollutant contents in the air.

Sverdlovsk. One of the three unfavorable conditions (air stagnation, relatively high temperature [t > - 10] with gentle winds, and its unfavorable direction [SE, S] combined with $P_{n-1} > 0.25$). Twelve days with these conditions include all of the situations of a dangerous pollutant content in the air.

Chita. Inversion near the ground and calm or existence of a very gentle transfer (wind speed 0 - 1 m/sec.) from N, NE, E and SE excluding the coldest days ($t < -30°$) with $P_{n-1} > 0.15$. During the two winter seasons, a total of 22 days were found that had these conditions, and they include all instances of the most intensive pollutant content in the air.

2. Dangerous accumulations of pollutants in the air in all of the cities in question were observed with a decrease in the wind speed to values less than 1 m/sec., and formation of calm conditions provided that on the previous day $P_{n-1} > 0.25$.

On the basis of the facts stated above, there is a possibility in each of the cities during the winter season to issue approximately 10 forecasts of a dangerous concentration of pollutants in the air, on the basis of which the city authorities must take measures to reduce emissions of pollutants into the air.

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